

# CONSOLIDATION OF FLAKEBOARD MATS UNDER THEORETICAL LABORATORY PRESSING AND SIMULATED INDUSTRIAL PRESSING

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## ABSTRACT

To achieve a more fundamental understanding of material behavior during the pressing process, a radiation-based system for measuring density of wood composite mats during consolidation is used to build *in-situ* cross-sectional density distributions of flakeboard mats with pressing time. The fundamentals of densification within flakeboard mats during hot and cold pressing are discussed in this paper. The pressing schedules included theoretical laboratory pressing schedules and schedules simulating industrial pressing. All tests were conducted at either ambient or 204°C temperature. The results include stress relaxation of flakeboard mats during cold and hot pressing, stress-strain behavior, *in-situ* density-strain behavior, and *in-situ* cross-sectional density distributions of flakeboard mats with pressing time. Results of laboratory studies indicate that the stress relaxation during hot pressing after the press reached final position was much quicker than during cold pressing. The observed stress-strain responses of flakeboard mats in hot pressing and cold pressing were similar, characterized by a long stress plateau followed by a rapid increase in stress and an immediate fall-down after the press reached final position. The process to simulate the industry operation resulted in another stress plateau. The stress-strain responses of flakeboard mats were characterized by a long stress plateau followed by a rapid increase in stress, and an additional high stress plateau followed by an immediate fall-down after the press reached final position. There was no clear indication that the maximum gas pressure attained is affected by press closing time.

**Keywords:** Densification, consolidation, density profile, compression, *in-situ* measurement, flakeboard, pressing, radiation, moisture, bonding, resin, unsteady state.

## INTRODUCTION

Hot pressing is a process of pressing a mat between hot platens or hot rollers of a press to compact and set the mat structure by simultaneous application of heat and pressure. One of the major objectives of hot pressing is to achieve a designed panel density and thickness. Hot pressing also results in the spatial density distribution within a panel, especially

the vertical density distribution (Harless et al. 1987; Kelly 1977; Wang 1986, 1987; Winistorfer et al. 1998, 2000; Winistorfer and Wang 1999). The density changes during hot pressing have been characterized by many terms, for example consolidation, compaction, compression, and densification. Wang and Winistorfer (2000) indicated that the vertical density profile of OSB is formed from a combination of actions that occur both during consolidation and also after the press has reached final position (i.e., thickness). The term “densifica-

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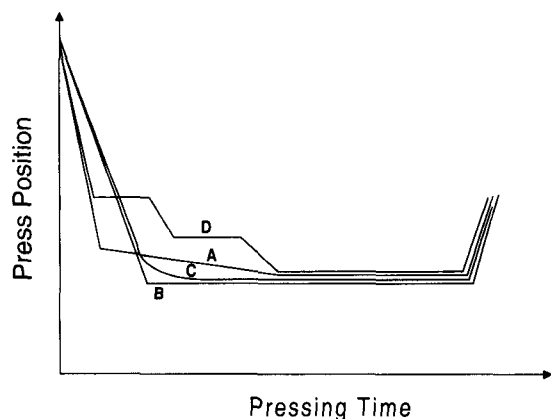


FIG. 1. Schematic diagrams of platen position during hot pressing using different pressing schedules. Schedules shown are: A creep closing schedule for MDF pressing, B theoretical one-step pressing schedule, C typical OSB industrial pressing schedule, and D three step-closing schedule for both OSB and MDF pressing.

tion" will be used throughout this paper to explain the density change within a mat during the whole pressing cycle.

The resulting shape of the density profile after pressing is influenced by three major factors: furnish moisture condition, mat structure, and the pressing environment. There are many underlying material and processing factors that can impact the formation and changes in the density profile. Pressing condition parameters include press closing time, press type, press temperature, press opening schedule, and mat structure.

To achieve a more fundamental understanding of material behavior during the pressing process, several researchers have investigated and described the effects of mat structure on composite performance (Steiner and Dai 1994; Lang and Wolcott 1996a). Other researchers have modeled the compressive stress-strain behavior of many natural and synthetic cellular materials (Wolcott 1989; Dai and Steiner 1993; Lang and Wolcott 1996b; Lenth and Kamke 1996a, b). The experimental results from the authors (Wang and Winistorfer 2000) showed not only stress-strain behavior, but also *in-situ* density-strain behavior.

Some stress-strain models were based on

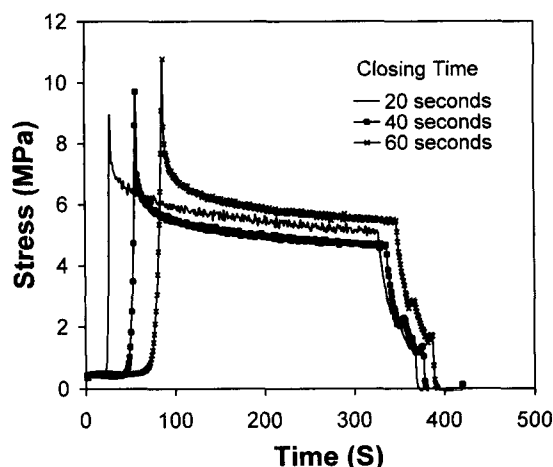


FIG. 2. Stress relaxation of flakeboard mats during cold pressing.

cold pressing and some other references did not clearly indicate that stress-strain behavior models were based on hot pressing or cold pressing (Dai and Steiner 1993; Lang and Wolcott 1996a, b). Heating does increase plasticization of wood and consequently affects the stress-strain behavior of the mat. No publication addressed a comparison of the effect of hot and cold pressing on the stress-strain behavior of the mat.

Figure 1 shows schematic diagrams of platen position during hot pressing. Schedule B in

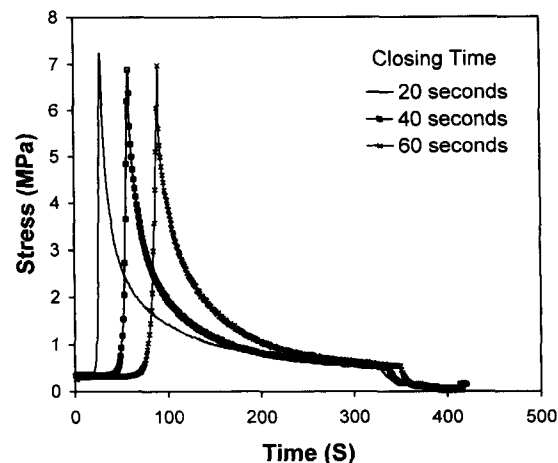


FIG. 3. Stress relaxation of flakeboard mats during hot pressing.

Fig. 1 represents a typical pressing schedule used by many researchers. Schedule B is an ideal hot-pressing schedule, which is typically reflected by a continual closing period under a constant closing speed and final press position period. However, industrial pressing schedules are more complicated than schedule B. The position of the moving platen is generally determined by the computer-based position-control system or pressure-control system. The pressure-control system is commonly used in plywood production. Schedule C in Fig. 1 is a typical pressing schedule used in OSB production. Industrial pressing using the position-control system does not always mimic laboratory press closing due to hydraulic system limitation. The press quickly closes to a position near final panel thickness, and then closing speed slows as the press reaches maximum pressure. While the press maintains maximum pressure, press platen movement is dependent on wood plasticization and further densification. In order to manipulate the end-product density profile attributes, other pressing schedules have been or will be used in the panel industry. For instance, schedule A includes a creep closing for MDF pressing (Park et al. 1999), and schedule D is a step-closing schedule for both OSB and MDF pressing (Wang et al. 2000a–c).

In this report, the fundamentals of densification within flakeboard mats during hot and cold pressing are discussed. The pressing schedules included theoretical laboratory pressing schedules and a schedule simulating the industrial pressing operation.

#### MATERIALS AND METHODS

##### *Mat preparation*

Aspen OSB furnish was procured from an industry mill and was conditioned to 7.0% moisture content. The target panel density was 0.608 g/cm<sup>3</sup>, and target panel thickness was 18.3 mm. Mats measured 356 mm by 356 mm, 432 mm by 432 mm, or 560 mm by 560 mm for hot pressing and 152 mm by 356 mm for cold pressing. There was no flake orientation

during mat forming. A commercial liquid phenol-formaldehyde resin was applied to the furnish at a rate 3% solids based on oven-dry wood weight in a rotating blender. A 1% wax application was used. The prepress moisture content of furnish was 9.8%.

A special mat-forming technique was used that incorporates a collapsible forming box, in which the mat is formed between two pieces of OSB panel material. The mat is then trimmed to final desired size while it is held prepressed between the OSB panel material. This technique allows for trimming the loose edge of the mat prior to pressing and was developed specifically for use with our in-press radiation monitoring system that requires a well-formed mat edge for enhanced *in-situ* radiation measurement accuracy.

##### *Pressing and measuring conditions*

All mats for hot-pressing experiments were produced with a platen temperature of 204°C, a pressing cycle of 360 s, and press closure time of 20, 40 or 60 s. The position of the moving platen is determined by a programmable logic position-control system. The other mats for cold-pressing experiments were produced at room temperature, a pressing cycle of 360 s, and press closure time of 20, 40, or 60 s. Closure time was defined as the time required to reach final position from the initial contact of the mat with the upper platen for the up-acting press. In order to simulate industrial pressing, 432-mm by 432-mm (marked as schedule A) and 560-mm by 560-mm (marked as schedule B) mat sizes and a 20-s closing time were chosen based on the preliminary experiments.

The three *in-situ* radiation beams for density measurements during hot pressing were located at three different positions of the mat thickness for each closing time, respectively (Winistorfer and Wang 1999; Winistorfer et al. 1998, 2000). A gas-pressure probe with a thermocouple was placed at the center of the mat cross section. The press hydraulic pressure was also recorded for each mat. The press con-

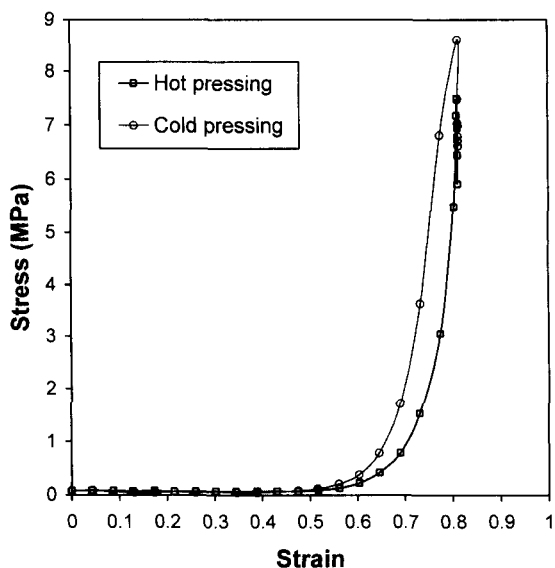


FIG. 4. Stress-strain relationships for cold and hot pressing at the 20-s closing time.

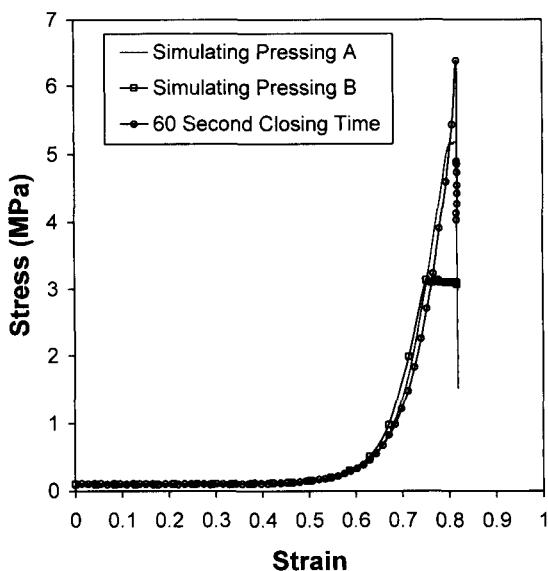


FIG. 5. Stress-strain relationships for the 60-s closing time, simulating schedule A (36-s real closing time) and B (88-s real closing time).

trol system, radiation monitoring system, and press monitor system allow radiation count data, press position, ram pressure, gas pressure, and temperature to be recorded in real time.

To measure *in-situ* density changes through more of the mat cross section than allowed by a single scan using the fixed-position radiation beams, the three fixed radiation beams were repositioned in slightly different locations for subsequent press runs on identical mats. The *in-situ* radiation beams were located at positions of 16.3%, 50%, and 83.7%; 29.3%, 58.7%, and 88%; and 20.6%, 50%, and 79.3%, respectively.

#### RESULTS AND DISCUSSION

##### *Stress relaxation of flakeboard mats during cold or hot pressing*

Figure 2 shows the average stress reading recorded during cold pressing for each of the three closing times. The relaxation curves displayed for the various closing times were all of a similar nature: rapid stress development and characteristic stress relaxation after the press reached final position or thickness. As

the closing time increased from 20 s to 60 s, the counter pressure (i.e., resistance of the mat to compression force) increased. Wood is a heterogeneous material that is composed of anisotropic cells. When wood is compressed, both elastic collapse and fractures will occur in the cell walls. The quicker press closing times result in quicker status changes from elastic collapse to fractures in the cell walls

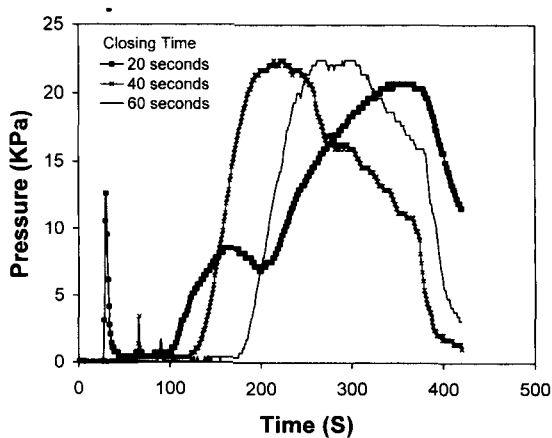


FIG. 6. Gas pressures of flakeboard mats during hot pressing.

and consequently result in a lower pressure to reach the final panel thickness.

Figure 3 shows the average stress reading recorded during hot pressing for each of the three closing times. Stress relaxation during hot pressing after the press reached final thickness occurred sooner than during cold pressing. The stress on the mat needed to maintain the final position during hot pressing decreased 73.0% for the 20-s closing time, 70.7% for the 40-s closing time, and 68.2% for the 60-s closing time from the peak point 40 s after the press reached final position, respectively. By comparison, the stress on the mat during cold pressing decreased only 30.7% for the 20-s closing time, 43.0% for the 40-s closing time, and 41.4% for the 60-s closing time from the peak point 40 s after the press reached final position, respectively. Compared to the stress relaxation of hot-pressed particles (Adcock and Irle 1996), stress relaxation of the mat during hot pressing after the press reached final thickness occurred more quickly than that for the individual particles. This implies that stress relaxation of the mat during hot pressing is not only the result of wood plasticization, but is also affected by horizontal mass movement.

Figure 3 also clearly shows that the press runs carried out at the 204°C temperature fostered plasticization of wood furnish, and therefore the peak stress exhibited is significantly lower than the cold pressing. The peak stress during hot pressing slightly decreased as the press closing time increased. The long closing time causes the mat surface layers to be warmer before the press reaches final position and consequently results in high plasticization of the surface layers. As a consequence of wood plasticization, stress relaxation should result in significantly lower counter pressure. This implies that the longer closing time helps increase core temperature before the press reaches final position and consequently decreases the peak stress.

#### *Stress-strain behavior*

The compressive stress-strain relationships of flakeboard mats for hot and cold pressing

for a 20-s closing time are shown in Fig. 4. The observed stress-strain responses of flakeboard mats in hot and cold pressing were similar, characterized by a long stress plateau followed by a rapid increase in stress and an immediate fall-down after the press reached final position. The long stress plateau resulted from collapse of between-flake voids. Both mats in cold and hot pressing showed a similar stress-strain response in the plateau region, which continues to a strain level of approximately 0.52.

The increased rates in stress corresponding to densification of the wood component were different for hot and cold pressing (Fig. 4). A hot-pressed mat will tend to be more plastic than a cold-pressed mat, thus requiring less compressive stress in the early stages of consolidation and achieving a higher strain before densification begins. The peak stress in the hot mat when the press reached final position was 7.49 MPa and 14.9% less than 8.61 MPa of the cold mat.

The compressive stress-strain relationships for flakeboard mats with a 60-s closing time and simulating the industrial pressing operation are shown in Fig. 5. The observed stress-strain responses of flakeboard mats with a 60-s closing time were still characterized by a long stress plateau followed by a rapid increase in stress and an immediate fall-down after the press reached final position. The two processes to simulate the industrial pressing operation resulted in an additional plateau. The stress-strain responses of flakeboard mats were characterized by a long stress plateau followed by a rapid increase in stress, another high stress plateau followed by an immediate fall-down after the press reached final position. The period of high stress plateau was affected by wood plasticization resulting from heat transfer.

#### *Gas pressure*

The results for the measured mat gas pressures and temperatures at the core layer are shown in Figs. 6 and 7. A longer press closing

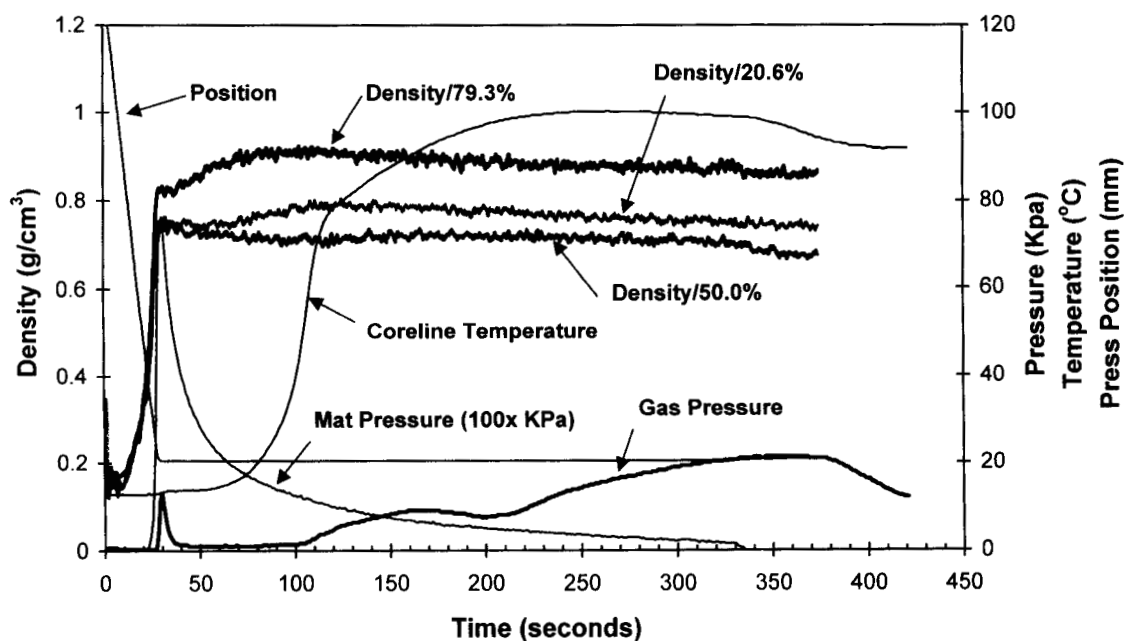


FIG. 7. *In-situ* density profiles and pressing pressure in the flakeboard mat using the 20-s closure time.

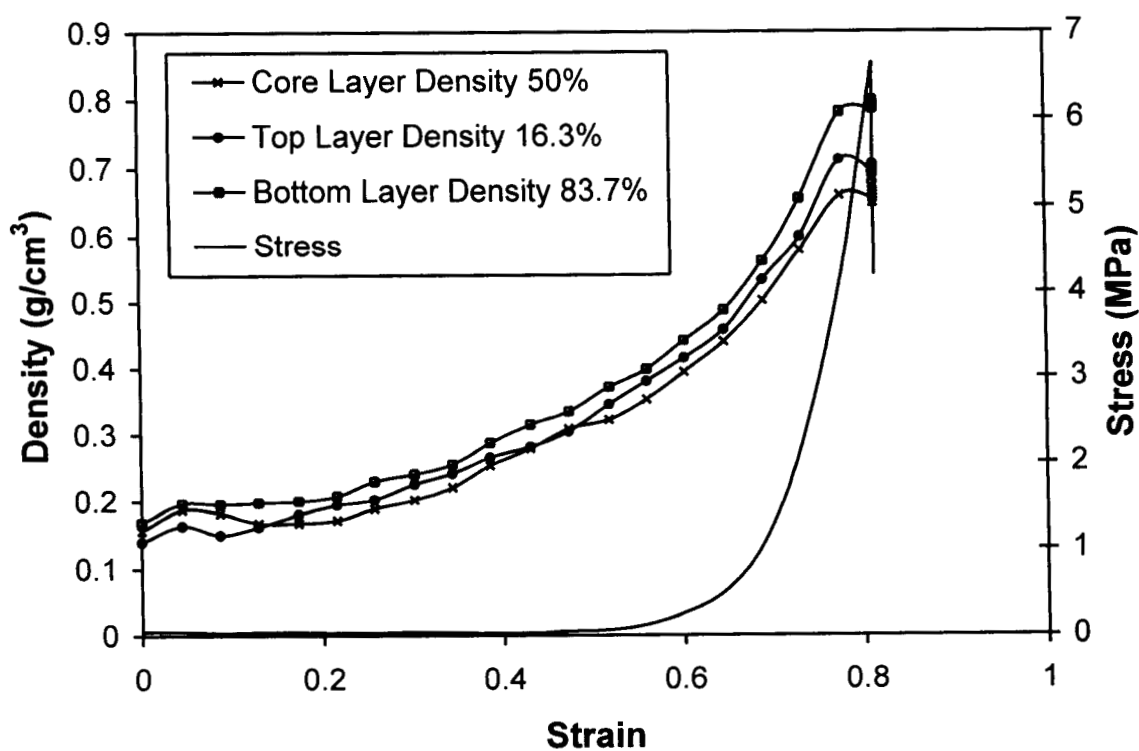


FIG. 8. Stress-strain and *in-situ* densities-strain relationships for the 20-s closing time.

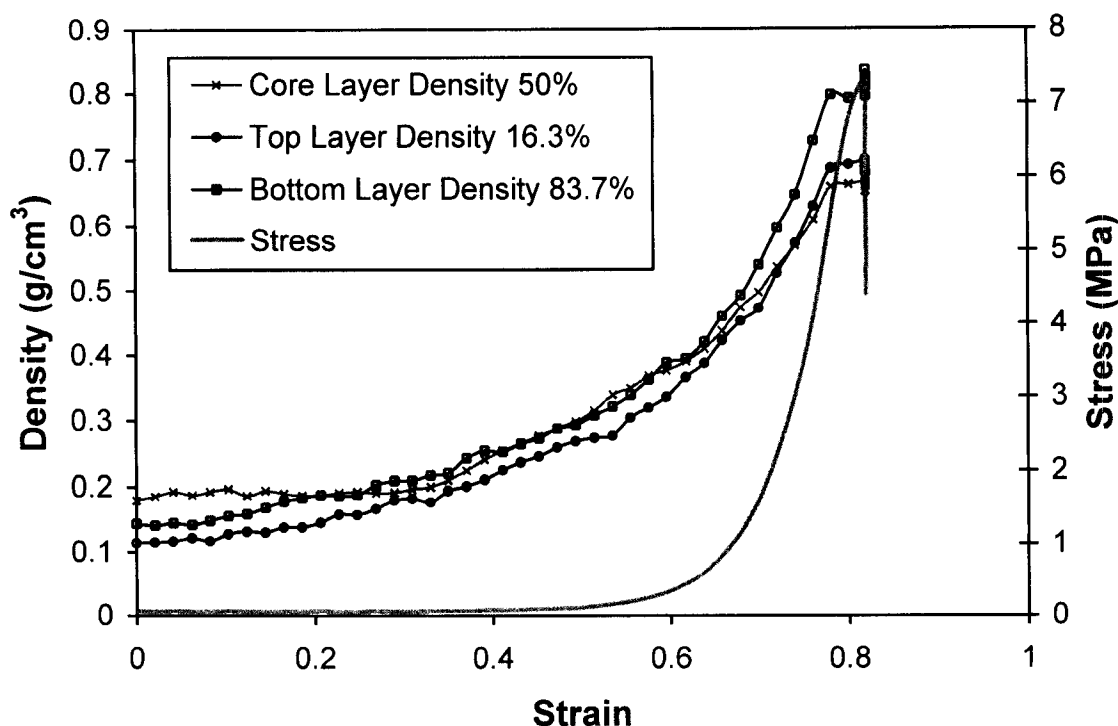


FIG. 9. Stress-strain and *in-situ* densities-strain relationships for the 40-s closing time.

time resulted in a delay of the increase of gas pressure. There was no clear indication that the maximum gas pressure attained is affected by press closing time. This result is similar to Kamke and Casey's results (Kamke and Casey 1988).

Gas pressure shows a minor peak at the time of press closing due to air entrapment. Figure 7 shows that a minor peak occurred when the press reached final position. The press closing time affects both location and maximum gas pressure of the minor peak. A longer press closing time resulted in a delay of the increase of the minor peak gas pressure and also decreased the maximum gas pressure due to air entrapment. The maximum gas pressure for the 20-s closing time due to air entrapment was 12.6 KPa, which was 60.9% of the 20.7 KPa gas pressure due to the generation of water vapor. Conversely, the maximum gas pressure for the 60-s closing time due to air entrapment was 1.76 KPa, which was only 8.5% of the 20.7 KPa gas pressure due to the

generation of water vapor. This means that the longer press closing time allows more air escape through the edges of the mat and consequently results in a lower gas pressure due to air entrapment.

#### *In-situ density-strain behavior*

Characteristic mechanical response for flakeboard mats in compression and resulting *in-situ* densities are shown in Figs. 8–11. Figure 8 shows that the core layer density was higher than the top layer density when the press started to close. When the strain was greater than about 0.18, the core layer density became lower than the top layer density, except during the strain range 0.45–0.48. Although measurement error is one possible reason for this discrepancy, the difference could be explained as follows. During the initial stage of compression, density develops from void removal instead of transverse compression. *In-situ* density for the top, core, and bot-

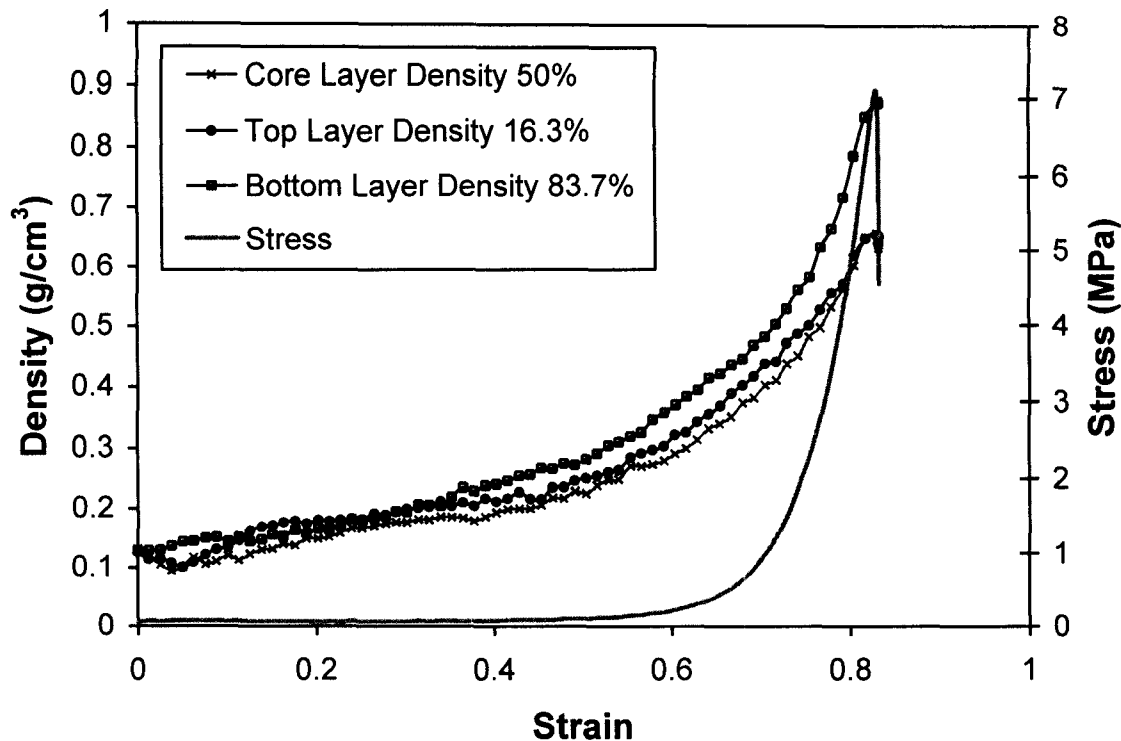


FIG. 10. Stress-strain and *in-situ* densities-strain relationships for the 60-s closing time.

tom layer reflects the bulk density of the mat at the same position, respectively. The bulk density of the whole mat can be affected by the magnitude of bow, cup, and twist of the individual strands. The in-press radiation system utilizes nuclear sources and electronic detection equipment to measure the relative amount of radiation passing through three horizontal planes in the wood mat as a measure of mat density. A collimated beam of radiation is transmitted in a horizontal plane from a source, through the mat, to the detector on the opposite side of the press. The radiation beam size is 0.16 cm in the vertical direction and 4.45 cm in the horizontal direction (Winistorfer et al. 1998, 2000). The average thickness of the aspen flakes was 0.061 cm. Each radiation beam passes through two or three strands in the vertical direction. During the initial stage of compression, strand bending will result in relative position changes of individual strands in the spatial mat structure. Conse-

quently, some strands or partial strands move into the radiation beam zone and other strands may move out of the radiation beam zone. This means that the radiation beam does not always pass through the same strands in the limited mat width. The above symptom during pressing small mats will be more significant than when pressing large mats as *in-situ* density is a mean measurement through the mat width.

Figure 8 shows that during nonlinear cellular collapse, *in-situ* densities using the 20-s closure time tended to increase at the same rate before the strain reached 0.74. The rate of density increase among the three layers showed different trends after the strain reached 0.74. Even the core layer density and top layer density started to decrease at the end of the press closing period. At final closure position at 20 s, maximum density and minimum density were achieved in the bottom layer and the core layer, respectively. Figure 9 shows stress-



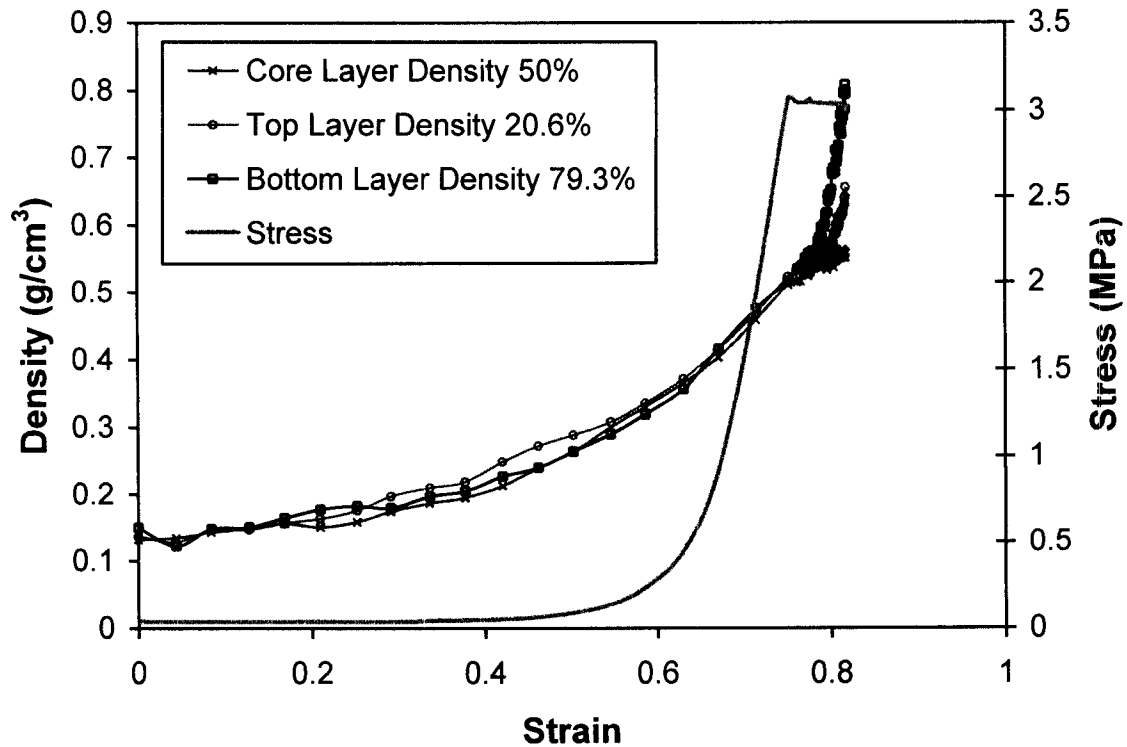


FIG. 11. Stress-strain and *in-situ* densities-strain relationships for simulating pressing schedule B (88-s real closing time).

strain and *in-situ* densities-strain relationships for the 40-s closing time. At the point of about 0.78 total strain, a distinct elbow was noted in each of the *in-situ* density profiles. However, compared to the 20-s closing time (Fig. 8), the core layer stopped increasing in density and did not decrease at the end of the press closing period; the top layer slightly continued to increase and the bottom layer significantly increased in density. When the press closing time increased to 60 s, the distinct elbow in the *in-situ* density-strain relationship was nearly eliminated and no layer showed a density decrease (Fig. 10). This implied that the press closing time significantly affected the final cell-wall densification stage. The longer press closing time resulted in a warmer core layer before the press reached the final position. No distinct elbow in the *in-situ* density-strain relationship was noted during the 200-s closure period (Wang and Winistorfer 2000).

The interesting *in-situ* density-strain relationships occurred during experiments to simulate the industrial pressing operation (Fig. 11). The process to simulate the industrial operation resulted in a high stress plateau. The peak stress was 3.0 MPa, which was much less than 6.7 MPa for the 20-s closing time schedule. While the press maintained 3.0 MPa peak stress, wood plasticization, resulting from heat transfer, resulted in continual strain development. Bottom layer density increased much quicker than the top layer and core layer due to a temperature gradient through the mat thickness. The top layer density increased faster than the core layer. This implied that a pressure-control pressing schedule easily results in a steep density profile, which has a high face density and low core density.

The density of different layers did not show significant changes immediately upon reaching the peak stress value. The top *in-situ* ra-

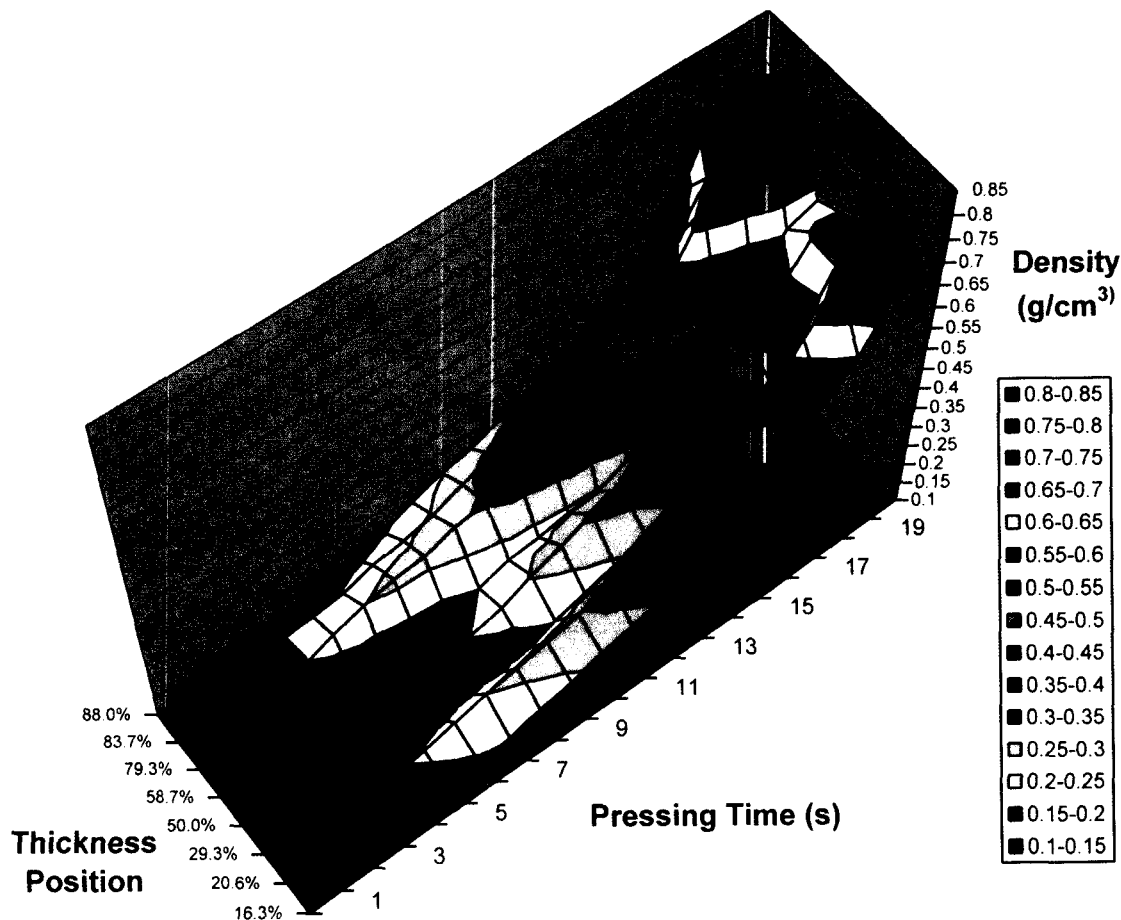


FIG. 12. *In-situ* cross-section density distribution during consolidation period for the 20-s closing time. Each data point represents an average at a 0.7-s interval calculated from the real-time data taken as eight measurements per second.

diation beam for density measurements during hot pressing was positioned at 20.6% of the mat thickness. It is possible for the outside mat layer to have had a faster rate of density rise. Also shown in Fig. 11 is that while the press maintains the 3.0 MPa peak stress, differential stress relaxation in the mat and nonuniform stress relaxation are reflected in the *in-situ* density measurement.

#### *In-situ density changes through mat thickness*

Figures 12 and 13 show *in-situ* density distributions of flakeboard mats with a 20-s closing time. Starting with an initial mat bulk den-

sity of 0.1 to 0.2 g/cm<sup>3</sup> (Fig. 12), the density through the mat thickness began to increase quickly in the press cycle. The low density of the two core areas increased within 6 s into the next density range (Fig. 12). After 4 s, the 0.2-0.25 g/cm<sup>3</sup> density developed at both of the mat surface areas, implying that uniform compression of the mat had finished and the period of nonuniform compression had begun (Wang and Winistorfer 2000). The *in-situ* density of the location 20.6% on the top side of the mat and the location 79.3% on the bottom side of the mat always started to increase earlier than other locations. A typical density gradient through the mat thickness, reflected by

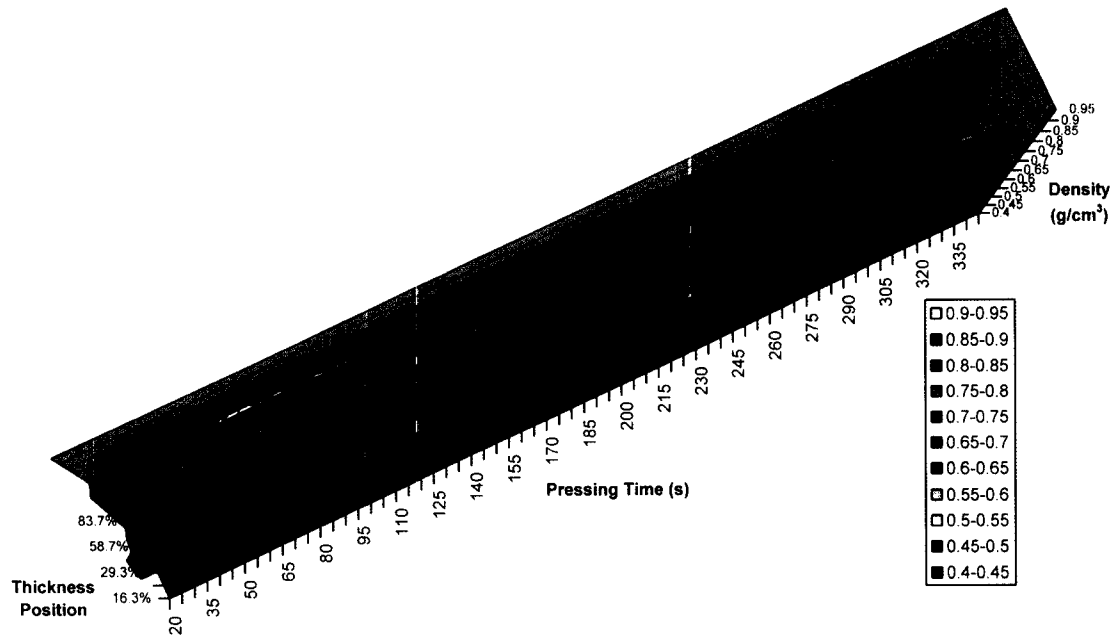


FIG. 13. *In-situ* cross-section density distribution during adjusting period while press maintains final position. Each data point represents an average at a 5-s interval calculated from the real-time data taken as eight measurements per second (20-s closing time).

the presence of high density face layers and low density core layers within the mat, also started to form from this point. At the end of the closing period, a density profile through the mat thickness was formed.

Figure 13 shows *in-situ* cross-sectional density distributions of flakeboard mats for the time period from final position to the end of the cycle. During the adjusting period, there were several marked changes in the mat density. The highest 0.9–0.95 g/cm<sup>3</sup> density temporarily developed at the 79.3% monitoring location on the bottom side during pressing at the time period 70–130 s. Almost developing at the same time, the top side of the mat showed a marked density decrease and then increased to the original density level at the end of the pressing cycle. The *in-situ* density decreased from the 0.85–0.9 g/cm<sup>3</sup> range to the 0.8–0.85 g/cm<sup>3</sup> range on the bottom side of the mat, beginning at a time of 150 s and continuing to develop throughout the remainder of the pressing cycle.

#### CONCLUSIONS

Results of laboratory studies indicate that at the point of the final press-closure position, the counter pressure significantly increased during cold pressing as the closing time increased. The stress relaxation during hot pressing after the press reached final position was much quicker than during cold pressing. The peak stress during hot pressing slightly decreased as the press closing time increased.

The observed stress-strain responses of flakeboard mats in hot and cold pressing were similar, characterized by a long stress plateau followed by a rapid increase in stress and an immediate fall-down after the press reached final position. The process to simulate the industry operation resulted in another stress plateau. The stress-strain responses of flakeboard mats were characterized by a long stress plateau followed by a rapid increase in stress, and an additional high stress plateau followed by an immediate fall-down after the press reached final position.

There was no clear indication that the maximum gas pressure attained is affected by press closing time. The radiation-based system for measuring density of wood composite mats during consolidation is a useful tool to build *in-situ* cross-sectional density distributions of flakeboard mats with pressing time.

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